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Electrohydraulic linear actuator with two stepping motors controlled by overshoot-free algorithm

Andrzej Milecki *, Jarosław Ortmann

Institute of Mechanical Technology, Poznan University of Technology, ul. Piotrowo 3, 60-965 Poznań, Poland

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A B S T R A C T

The paper describes electrohydraulic spool valves with stepping motors used as electromechanical transducers. A new concept of a proportional valve in which two stepping motors are working differentially is introduced. Such valve changes the fluid flow proportionally to the sum or difference of the motors' steps numbers. The valve design and principle of its operation is described. Theoretical equations and simulation models are proposed for all elements of the drive, i.e., the stepping motor units, hydraulic valve and cylinder. The main features of the valve and drive operation are described; some specific problem areas covering the nature of stepping motors and their differential work in the valve are also considered. The whole servo drive non-linear model is proposed and used further for simulation investigations. The initial simulation investigations of the drive with a new valve have shown that there is a significant overshoot in the drive step response, which is not allowed in positioning process. Therefore additional effort is spent to reduce the overshoot and in consequence reduce the settling time. A special predictive algorithm is proposed to this end. Then the proposed control method is tested and further improved in simulations. Further on, the model is implemented in reality and the whole servo drive system is tested. The investigation results presented in this paper, are showing an overshoot-free positioning process which enables high positioning accuracy.

1. Introduction

Hydraulics has a long tradition, tracking back to XIX century. The first designs of mechanic-hydraulic servo drives were made before the First World War. They enabled to control the displacement of huge masses with a handy mechanical lever. In the fifties of XX century the first servo valve gave way to the development of electrohydraulic servo drives controlled by an electrical signal. The design of a servo valve, which is an interface between low energy electrical signals and high level hydraulic power, has enabled the creation of electrically controlled drive systems. Since the early eighties of XX century, the proportional valves have been designed and used in hydraulic drives more and more widely. In these valves the proportional DC electromagnets are used as electromechanical transducers. In comparison to servo valves, proportional valves are more cost effective, but they have worse parameters, such as accuracy and frequency response. In high accuracy positioning tasks it is necessary to use electromechanical transducer which enables to move the valve control spool with very small displacements, taking very little steps. However neither servo valves nor proportional valves enable to assure such spool movements with high frequency. Therefore in recently made research, also such elements like piezo actuators [1–4] or

* Corresponding author.
E-mail addresses: andrzej.milecki@put.poznan.pl (A. Milecki), jortmann@op.pl (J. Ortmann).

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synchronous motors [5,6] are used as valve electromechanical transformers. In paper [7] the new possible direction of valves development is proposed, namely the replacement of steel by plastic. Two prototype plastic-based hydraulic valves: the pressure relief valve and the on/off valve are described there. Within a low pressure range they perform comparably well to the elements which are traditionally made of steel and are available on the market. The authors presented the research that has been done on them so far, showing also problems associated with the application of plastics for the making of the valves. The paper [8] presents an advanced electronic control system suitable for application in mobile multifunctional hydraulic machine. The benefits of electronics integration with the hydraulic systems have been highlighted. The special focus is on the machine drives output torque control, which is crucial in many cases.

In the so called linear electrohydraulic amplifiers also stepping motors are used as electromechanical transformers [9–12]. These motors are nowadays offered by various manufacturers in a wide range of specifications and with different control circuits [13,14]. Stepping motor is able to make small rotary steps with a frequency reaching a few kHz, which enables to control the valve gaps cross section areas with high accuracy. Electrohydraulic drives with valves containing stepping motors used as electromechanical transducers, have been produced for more than twenty years but only by a few companies, like ACP&D Limited [15] or Victory Controls [16].

At Poznan University of Technology the investigations of applying stepping motors in proportional valves have been conducted across the last few years [17]. The first design was the electrohydraulic servo drive in which a ball screw was used as a feedback linkage. This design is presented in Fig. 1. The stepping motor (1) was applied as an initial element for spool displacement of four edge hydraulic amplifier (3). This spool was connected with stepping motor shaft by a coupling element (2) on one side, and through thread (4) to the valve body on the other. In this way the rotary movement of the spool was converted to a linear one, proportional to the number of stepping motor steps. It has caused the shifting of the spool and opening of the gaps between spool and body of the valve. This has further on resulted in the flow of oil between the hydraulic actuator chambers and the displacement of the piston and in turn has caused the revolution of a ball screw (5) which was connected to it. Because the ball screw revolution had the same direction as the revolution of the thread (4), this has caused the spool to come back to the initial position and to close the valve gaps. This type of a drive is called a linear electrohydraulic amplifier. During the research made at Poznan University of Technology such servo drive unit with mechanical feedback linkage and piston diameter of 140 mm was designed and built. The stepping motor applied in this design can make a step of 0.72° or 0.36°, which means 500 steps/rev or 1000 steps/rev. The spool valve diameter of hydraulic amplifier was 10 mm and its maximum displacement was $x_{max} = \pm 1$ mm. In this solution the valve was mechanically integrated with a hydraulic cylinder and with the ball screw, which effectively means that such a drive must be designed as a one-off solution per application.

Fig. 2 shows a different physical model of electrohydraulic proportional valve [18], in which a stepping motor (1) is used as an initial element for spool displacement of a four edge hydraulic spool amplifier. Such valve can be connected with almost any hydraulic cylinder, which is an important advantage in comparison with the solution presented in Fig. 1. The spool (3) is connected with the stepping motor shaft by an elastic coupling element (2). On the other side of the valve, the spool is connected to the valve body by its threaded ending (4), which turns the rotary spool displacement into linear. In this way the linear displacement is proportional to the number of stepping motor steps. The shifting of the spool results in opening or closing of the gaps (5) between spool and valve body.

The proportional valve with one stepping motor was designed especially for low and very low oil flow, thus electrohydraulic drive velocities are low (less than 1 mm/s.). In such case the phenomena that affect the drive's behavior are different than those during normal work, i.e. with velocities of more than few mm/s. One of the most important influence factors is contamination, because its particles can block the valve gaps. The proposed valve cannot be successfully used in drives which require obtaining higher speed (more than 10 mm/s) while assuring good dynamics and positioning accuracy. Therefore the application of two stepping motors working differentially is proposed in this article.

However, there is one important disadvantage of using the stepping motors: in order to fully open the valve, the stepping motor has to make thousands of steps, which may take even a few seconds. So, in order to improve the valve dynamics the

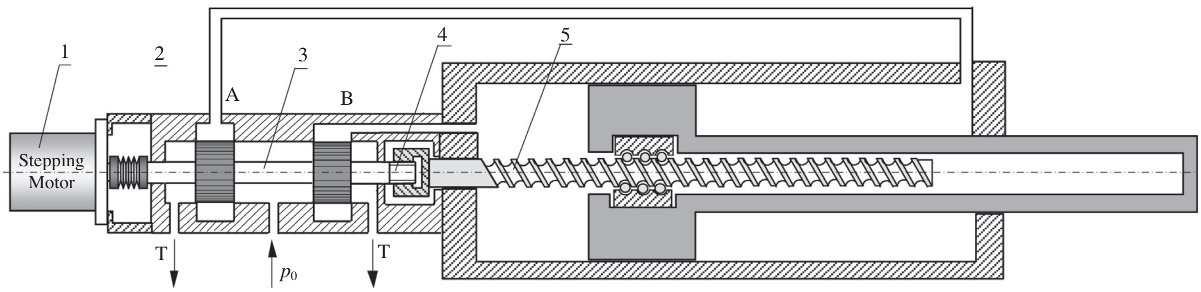

Fig. 1. Electrohydraulic servo drive with stepping motor and with mechanical feedback linkage, where: p_0 – supply pressure, T – tank ports, A, B – cylinder chambers ports.